# Sharing of the Angular Momentum between Electronic Subshells of Multielectron Ions Formed in Photoionization

O. Yenen, K. W. McLaughlin, and D.H. Jaecks
Department of Physics & Astronomy, University of Nebraska-Lincoln, Lincoln NE 68588-0111, USA

For physical processes involving more than two particles, conserved quantities such as energy, momentum, angular momentum can be shared in principle in an infinite number of ways. However, it is desirable, from a scientific point of view, to formulate broad organizing principles describing tendencies in sharing these conserved quantities among the constituents of a few-particle system. Atomic photoionization studies are ideal for gaining insight in these matters for that there is a large accumulated knowledge about atomic properties. As a convenient and accessible system, we have already successfully used high resolution polarization analysis of fluorescent radiation from $(Ar^+)^*$ to show that certain doubly excited states of Ar have a tendency to conserve their spherically symmetric cores during autoionization.[1]

In this abstract we will show that from the measurement of the polarization of the 476.5 nm fluorescence radiation produced by $3p^4\,[^3P]\,4p\ ^2P_{3/2}$ to $3p^4\,[^3P]\,4s\ ^2P_{1/2}$ transition in $Ar^+$, we obtain quantitative measures of how the different constituents of the residual excited atom share the single unit of angular momentum brought into the system by the ionizing photon. The quantitative measures in question are the total alignment coefficient $A_0^c(j)$ of the total angular momentum j of the excited ionic state, $A_0^c(L)$ of the total orbital angular momentum L of the excited ion, $A_0^c(L_c)$ of the orbital angular momentum $L_c$ and $A_0^c(S_c)$ of the spin $S_c$ of the optically inactive $3p^4$ $[^3P]$ core electrons, and, $A_0^c(\ell)$ of the angular momentum $\ell$ of the optically active 4p valence electron.[2]

In the experiment described here, an effusive atomic beam of Ar intersects the ionizing photon beam of the 9.0.1 beam line of ALS at right angles. The linear polarization axis of the synchrotron radiation is aligned along the atomic beam direction. The photoionization reaction can be represented as

$$h\nu_0 + Ar \rightarrow (Ar)^{**} \rightarrow Ar^+(3p^4\,[^3P]\,4p\ ^2P^o_{3/2}) + e^-$$
$$\longrightarrow Ar^+(3p^4\,[^3P]\,4s\ ^2P^o_{1/2}) + 476.5\text{ nm}.$$

We scan the energy of the ionizing photons from 35.6 to 38.3 eV with a resolution of $E/\Delta E \approx 12{,}700$. The intensities of the fluorescent light at 476.5 nm, polarized parallel ($I_\parallel$) and perpendicular ($I_\perp$) with respect to the polarization axis of the incident synchrotron radiation are measured perpendicular to the collision plane determined by the momenta of the Ar atoms and the incident photons. From these measurements we determine the intensity $I(90) = I_\parallel + I_\perp$ and the polarization $P(90) = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)$ of the satellite line. The total alignment coefficient $A_0^c(j)$ which is a measure of the distribution of different $|m_j|$ sublevels is obtained from the measured polarization P(90) using [3, 4]

$$A_0^c(j) = \frac{\langle 3j_z^2 - j^2 \rangle}{j(j+1)} = \frac{\sum_{m_j} \sigma(j, m_j)[3m_j^2 - j(j+1)]}{j(j+1)\sum_{m_j} \sigma(j, m_j)} = \frac{4\,P(90)}{h^{(2)}\,[3 - P(90)]} \qquad (1)$$

where $h^{(2)}$ is a constant depending on the total angular momenta of the initial and final states.

To determine the alignments of different angular momenta of the constituents of the excited residual ion we use the angular momentum decoupling rules. We denote by $|\alpha, j\rangle$ the excited $3p^4\,[^3P]\,4p\ ^2P^o_{3/2}$ states of $Ar^+$, where j is the total angular momentum and $\alpha$ all other quantum numbers to completely characterize the state. $|\alpha, j\rangle$ can be expanded in terms of its magnetic substates

$$\left|\alpha, j\right\rangle = \sum_{m_j} a_{m_j}\left|\alpha, j\, m_j\right\rangle \tag{2}$$

The coefficients $a_{m_j}$ contain the dynamical information of the double photo-excitation and the following autoionization to form the satellite states. For our case where j=3/2, $|a_{m_j}|$ can be calculated from the measurements and their squared magnitudes give the magnetic sublevel cross sections normalized to their sum.

The excited $3p^4\,[^3P]\,4p\ ^2P^o_{3/2}$ states of $Ar^+$ are best described by a LS-coupling scheme [4] and **j** = **L**+**S**. Therefore, one can decouple the $|\alpha, j m_j\rangle$ into total orbital **L** and total spin **S** angular momenta eigenstates. Omitting $\alpha$, the expansion is

$$\left|j m_j\right\rangle = \sum_{M_L M_S}\left\langle L M_L\, S M_S \middle| j m_j\right\rangle \left|L M_L\right\rangle \left|S M_S\right\rangle \tag{3}$$

where $\langle L M_L\, S M_S | j m_j\rangle$ are Clebsch-Gordon coefficients. The probability of forming a satellite state with given total orbital angular momentum quantum number L and magnetic quantum number $M_L$ is

$$\left|\left\langle L M_L \middle| \alpha, j\right\rangle\right|^2 = \frac{\sigma(L M_L)}{\sigma_{total}} \tag{4}$$

where $\sigma(L M_L)/\sigma_{total}$ is the relative cross section for forming a satellite state with total orbital angular momentum L and magnetic quantum number $M_L$ . Using equations (2) and (3) one can express these cross sections in terms of the dynamical parameters $a_{m_j}$. We can also express the alignment $A_0^c(L)$ due to the orbital motion of the electrons, in a manner similar to eq. (1)

$$A_0^c(L) = \frac{\langle 3L_z^2 - L^2\rangle}{L(L+1)} = \frac{\sum_{M_L}\sigma(L, M_L)[3m_L^2 - L(L+1)]}{L(L+1)\sum_{M_L}\sigma(L, M_L)} \tag{5}$$

Substituting the $\sigma(L M_L)/\sigma_{total}$ cross sections in terms of the dynamical parameters $a_{m_j}$ in equation (5), we obtain

$$A_0^c(L) = \frac{1}{2}[|a_{3/2}|^2 - |a_{1/2}|^2 - |a_{-1/2}|^2 + |a_{-3/2}|^2\,] \tag{6}$$

Since the initial ionizing photon is linearly polarized, there is no circulation of electronic charge, which means the orientation parameter is zero, and the probability amplitudes for $m_j$ and $-m_j$ are the same i.e., $a_{m_j} = a_{-m_j}$. Since $|a_{m_j}| = \sigma(j m_j)/\sum_{m_j}\sigma(j m_j)$ we find

$$A_0^c(L) = \frac{5}{8}\,A_0^c(j) \tag{7}$$

The total orbital angular momentum L can also be decoupled into the orbital angular momentum $L_c$ of the $3p^4\,[^3P]$ core electrons and the orbital angular momentum $\ell$ of the 4p valence electron. Similarly, the total spin S=1/2 of the satellite state can be decoupled into the spin $S_c$ of the $3p^4$ [$^3$P] core and the spin s=1/2 of the 4p valence electron and their alignments can also be calculated. Following a procedure similar to the one described above, and using equation (7) we find

$$A_0^c(L_c) = -\frac{5}{16}\, A_0^c(j) = -\frac{1}{2}\, A_0^c(L) = A_0^c(\ell) \tag{8}$$

We have performed the **j**=**L**+**S** and **L** = $\mathbf{L_c}$ + $\ell$ decouplings for a variety of $Ar^+$ satellite states and in each case we found proportionality relations similar to eq. (8). The sign and the value of the proportionality constants depend on the satellite state.

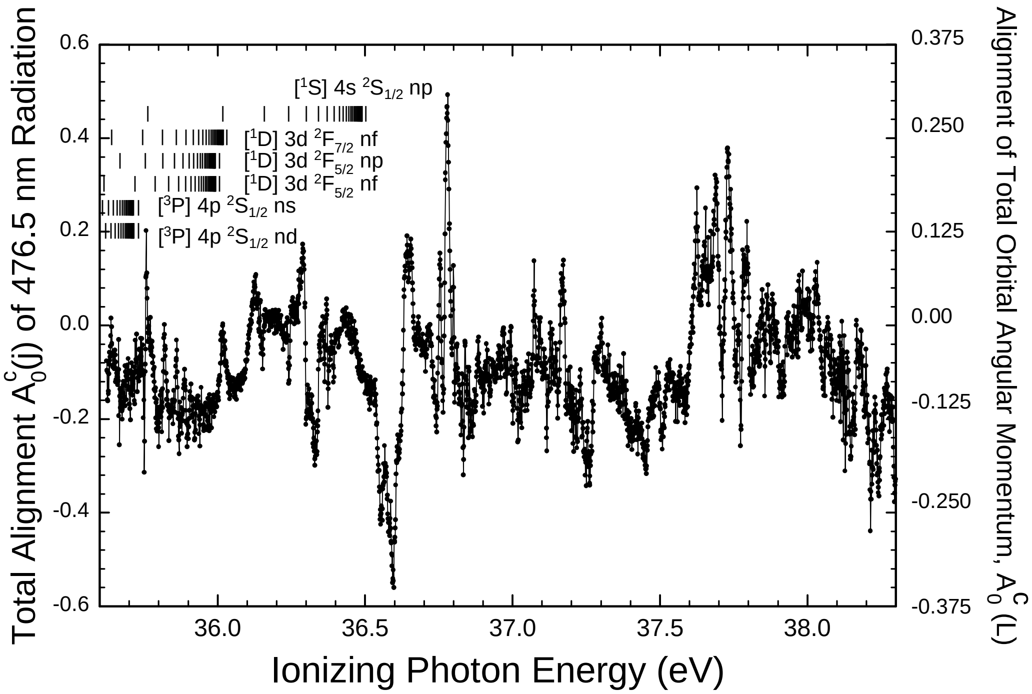


Figure 1**:** Th**e** alignment $A_0^c(L)$ of the total orbital angular momentum L is proportional to the alignment $A_0^c(j)$ of the total angular momentum j of the excited ionic state. Vertical lines denote the assigned doubly excited Rydberg series of Ar. Identification of doubly excited states above 36.6 eV is in progress.

Fig. 1 shows the alignment $A_0^c(j)$ of the total angular momentum and the alignment $A_0^c(L)$ of the total orbital angular momentum of the excited ionic state calculated from the measured polarization. Also shown on Fig. 1 are the positions of the doubly excited Rydberg series of Ar. Since the identification of the doubly excited states of Ar above 36.6 eV is still in progress, we did not show them on Fig. 1. One should note here that the extreme allowed values of $A_0^c(j)$ are ±0.8.

Fig. 2 shows the alignment $A_0^c(L_c)$ of the orbital angular momentum of the $3p^4$ [$^3$P] core and the alignment $A_0^c(\ell)$ of the 4p valence electron of the excited ionic state calculated using equations (8).

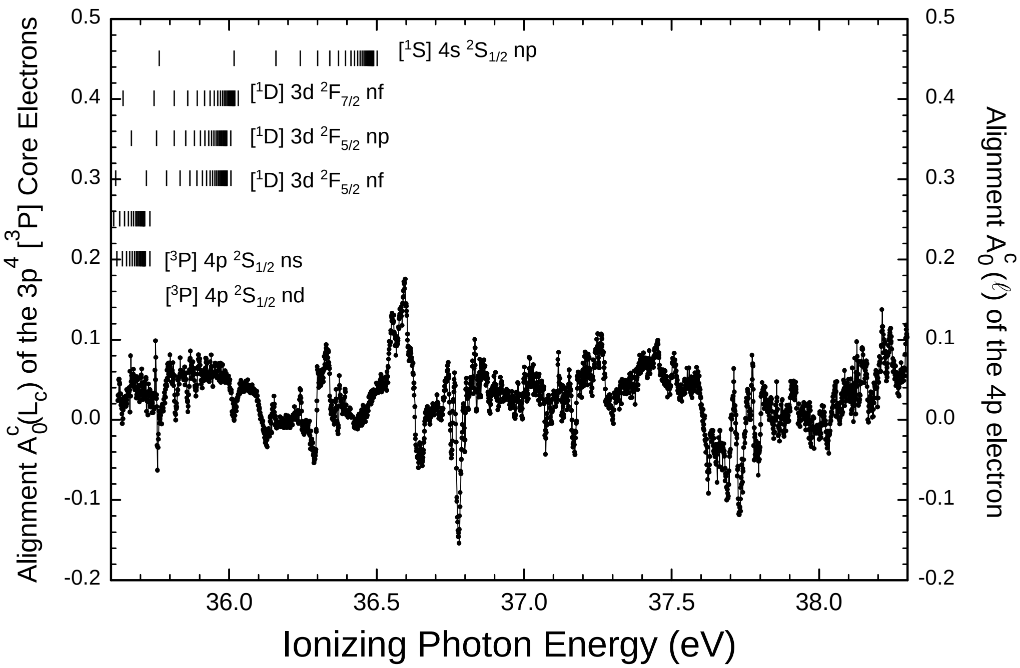


Figure 2: Alignment $A_0^c(L_c)$ of the orbital angular momentum of the $3p^4$ [$^3P$] core and the alignment $A_0^c(\ell)$ of the 4p valence electron of the excited ionic state.

In this abstract, we have shown that the combination of the characteristics of high resolution ionizing radiation from a third generation synchrotron source with the added information of polarization of fluorescent light leads to quantitative information about angular momentum sharing that cannot be obtained in any other way.

## REFERENCES


1. O. Yenen, K.W. McLaughlin, and D.H. Jaecks, Phys. Rev. Lett. **79**, 5222 (1997).
2. The alignments of the spin of the 4p valence electron and the total spin S of the excited ion are trivially zero.
3. B.W. Moudry, O. Yenen, D.H. Jaecks, and, J.H. Macek, Phys. Rev. A **54**,4119(1996).
4. U. Fano and J. Macek, Rev. Mod. Phys. **45**, 553 (1973)



This work is supported by the National Science Foundation under Grant No. PHY-941905



Principal investigator: Duane H. Jaecks, Department of Physics, University of Nebraska-Lincoln.
Email: djaecks@unlinfo.unl.edu. Telephone: (402) 472-3274